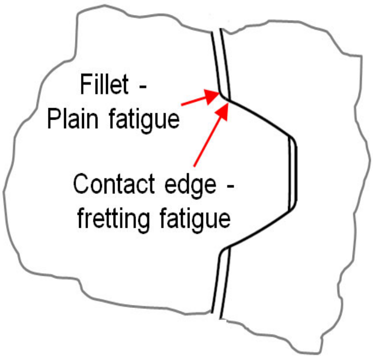
Comparison of different shaft-hub connection profiles considering fretting fatigue and plain fatigue performances



Shen, L. J.

The spline teeth is exposed to dangers of plain fatigue crack due to fillet bending and fretting induced crack near contact edge at the same time under 'no macro relative movement (between connection shaft and hub tooth)' running state. This paper compared the plain fatigue and fretting fatigue performances of different shaft-hub connection profiles.

1 Introduction

Under 'no macro relative movement (between connection shaft and hub tooth)' running state, the spline shaft-hub connection (SHC) teeth is exposed to dangers of plain fatigue crack due to fillet bending and fretting induced crack at the same time. Compared to the material engineering measurements such as surface treatment, coating, use of better materials etc., the structure optimization can improve the fatigue strength of spline teeth more economically, and is a more competent task for a mechanical engineer. This paper will discuss the competition of plain fatigue and fretting fatigue near teeth root at first and then the palliative measurements to both of them.

2 Plain/fretting fatigue 'Competition' in spline SHC teeth

Fig. 1 shows the distribution of fretting damage parameter (FDP, $FDP = \tau_{fric} \cdot s$ /1/) and fretting fatigue damage parameter (FFDP, $FFDP = \sigma_{\tan} \cdot \tau_{fric} \cdot s$ /1/) along teeth flank of involute spline shaft-hub connection under dynamic torque. The distribution of FDP along teeth flank is similar to the distribution of contact pressure, serious friction at both of the contact edges may lead to serious fretting wear but not bound lead to fatigue crack. The algebraic maximal value of

FFDP occurs near the start of contact, and after that, the value of FFDP changed from positive to negative. Though the author of FFDP model did not discuss the sign of FFDP value, the crack occurred at the point with maximal positive value of FFDP /1/. Many of the fretting fatigue studies are implemented in a 'fretting pad + uniaxial tensioned specimen' experiment configuration /2,3/, the normal stress in tangential direction of contact surface is always tension stress, so there's no need to discuss the sign of FFDP value in this kind of experiment configuration. But, in spline SHC, the tensile stress along the contact surface is generated by the contact load on the teeth flank. This implies that the tensile stress along the tangential direction of contact surface is one of the prerequisite of fretting fatigue crack in FFDP model. So, according to the distribution of FFDP along teeth flank, the only potential location of fretting fatigue crack is at the teeth flank contact edge near teeth fillet.

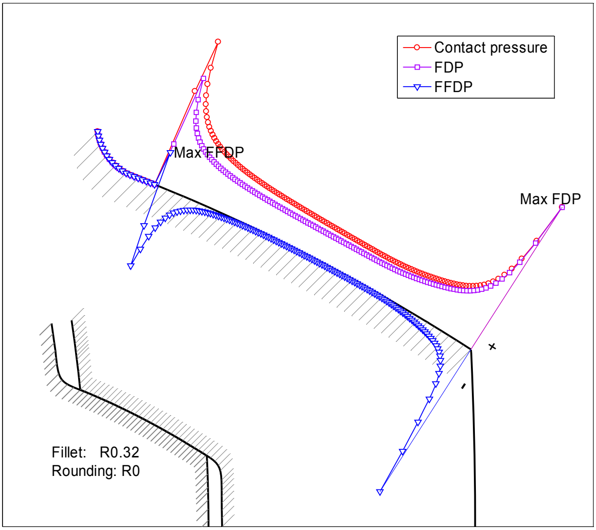


Fig.1: Distribution of FDP and FFDP (normalized by dividing respective maximal values) along involute spline teeth flank

At the same time, the critical plane multi-axial SWT /4,5/and FS /6/ plain fatigue prediction parameters are also implemented to the dynamically loaded spline teeth flank, the distribution of SWT and FS parameter along the shaft teeth flank are showed in Fig.2. The first peak values of SWT parameter and FS parameter occurred at the fillet of teeth, the second peak value occurred near the start of contact. Rather than the fretting fatigue crack location predicted by the FFDP model, the most possible location of plain fatigue crack predicted by SWT or FS parameter is at the fillet of involute spline teeth.

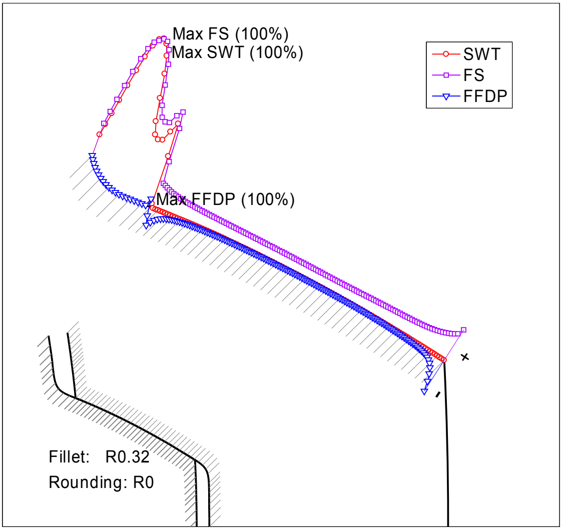


Fig.2: Distribution of SWT and FS (normalized along teeth flank, Fillet: R0.32; Rounding: R0

As discussed above, the FFDP predicted that the only potential location of fretting fatigue crack is at the teeth flank contact edge near teeth fillet, the SWT and FS parameters predicted that the most possible location of plain fatigue crack is at the fillet of involute spline teeth. Here comes the question that which one, plain fatigue crack at the fillet of spline teeth or the fretting fatigue crack near the start of contact will leads to the fracture of the spline teeth, we define it as a plain/fretting fatigue competition mechanism. Obviously, our concern is to minimize the danger of fretting fatigue near contact edge and plain fatigue at teeth fillet at the same time. The first intuition of structure optimization is to round the sharp contact edge for the purpose of alleviating stress singularity and abrupt stiffness change near contact edge or increase the radius of teeth fillet. Increase the radius of fillet greatly decreased the value of SWT and FS parameter but further increased the danger of fretting fatigue, because the teeth root becomes stiffer and gives rise to the micro slip at contact edge, as shown in Fig.3

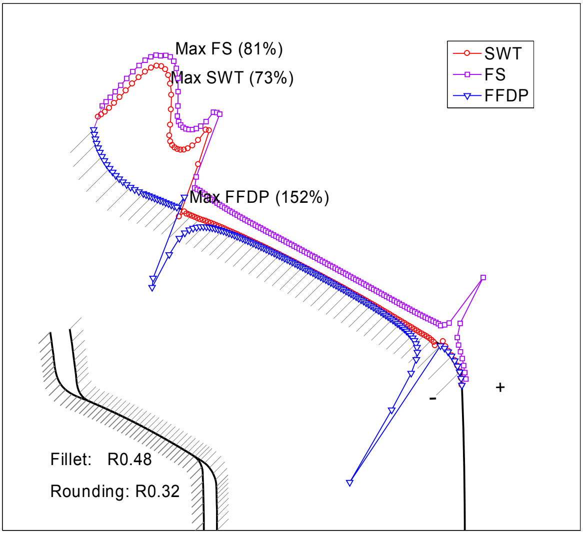


Fig.3: Distribution of SWT, FS and FFDP parameter (normalized) along teeth flank, Fillet: R0.48; Rounding: R0.32,

3 Comparison of involute spline and IMW complex cycloid profile

The complex cycloid profiles introduced by Ziaei, M. provided an alternative to the standard spline shaft-hub connections to transmit torque /7, 8/. The geometrically continuous contour of complex cycloid profile gets rid of the stress singularity and abrupt change of stiffness problem that greatly concerned in spline shaft-hub connections, and furthermore, it is hopefully to decouple the function centering from the function of torque transmission by profile optimization. Here, the plain and fretting fatigue prediction parameters will be also implemented in a group of complex cycloid profile in order to compare the plain/fretting fatigue performances with involute spline SHC under dynamic torque. Referred to the common equation introduced by Ziaei, M. /8/, a new group of complex cycloid profile is introduced here, named as IMW profile. Keeping the teeth number, the major radius, minor radius and the middle radius be the same with involute spline SHC, Fig.4 shows the shape of four IMW profiles with different pressure angles. According to the parameter equation of IMW complex cycloid profile, every involute spline SHC in DIN5480 can find several corresponding IMW profiles with different pressure angle following the above method.

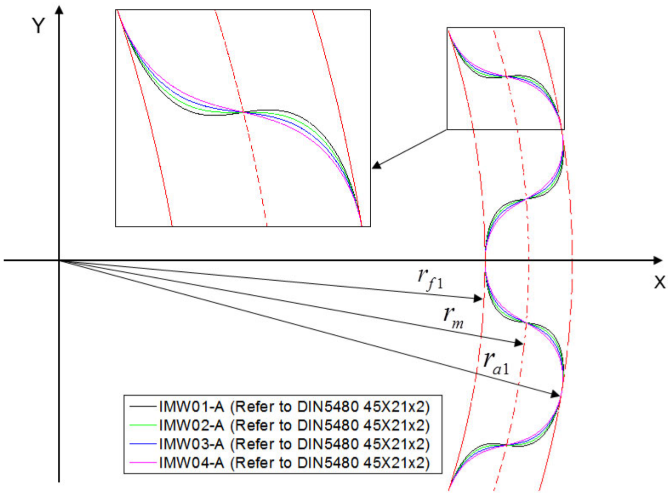


Fig.4: IMW01-IMW04 profiles referred to DIN5480 45x2x21
(r_{f1} =20.2, r_{a1} =22.3, $r_m = \left(r_{a1} + r_{f1}\right)/2$ =21.25)

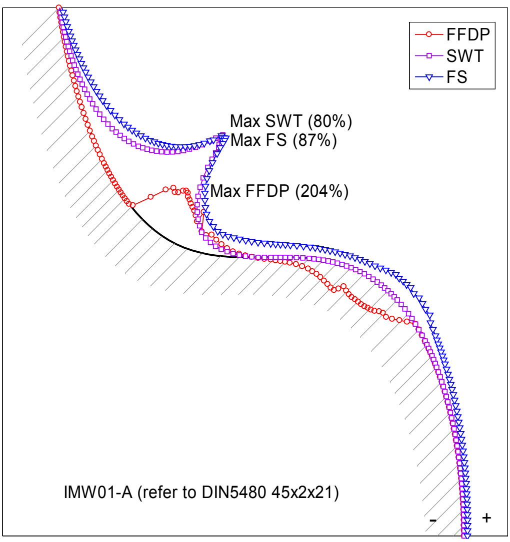


Fig.5: Distribution of SWT, FS and FFDP parameter along teeth flank of IMW01-A

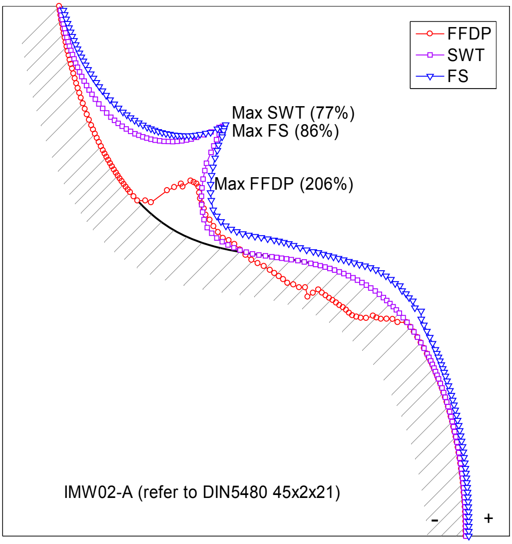


Fig.6: Distribution of SWT, FS and FFDP parameter along teeth flank of IMW02-A

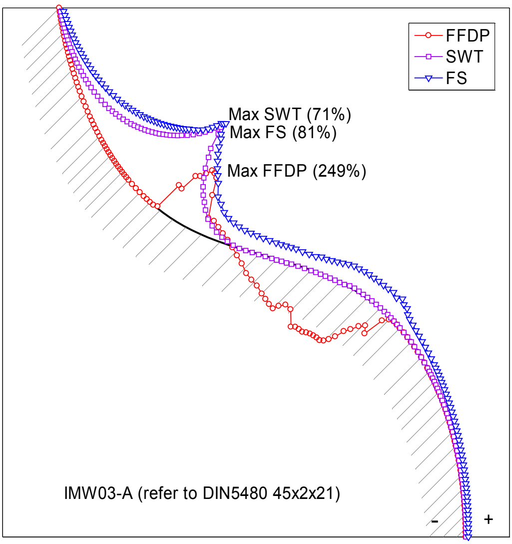


Fig. 7: Distribution of SWT, FS and FFDP parameter along teeth flank of IMW03-A

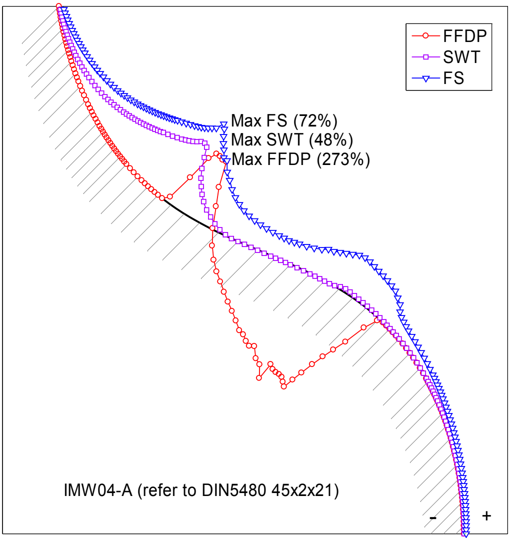


Fig.8: Distribution of SWT, FS and FFDP parameter along teeth flank of IMW04-A

Under the same dynamic load as that of involute spline SHC, Fig. 5-Fig.8 showed the distributions of SWT, FS and FFDP along teeth flank of these four IMW complex cycloid profiles. The profiles are rotated 180/21 degree around the axis in clockwise in FE analysis, so that the middle line of teeth meets the X axis of the coordinate system for the unity with involute spline teeth. One of the most great difference showed in these figures is that the maximal value of FFDP and plain fatigue prediction parameters SWT and FS both occurred at the teeth root (fillet), and the values of FFDP are much greater than that in involute spline teeth, this means that this type of complex cycloid profile is more sensitive to fretting fatigue compared with involute spline profile. At the same time, the danger of plain fatigue at teeth root is decreased, the value of SWT parameters decreased always much more than that of shear mode FS parameters. In the IMW04-A (refer to DIN5480 45x2x21) profile, the reduction of SWT value reached 52% and the reduction of FS value is 28%, that means the plain fatigue crack will change from tensile mode dominated to shear mode dominated with the increase of pressure angle. At the same time, the danger of fretting fatigue is increased with the increase of pressure angle.

4 Conclusion

The involute spline teeth are exposed to danger of plain fatigue at fillet and fretting fatigue at the contact edge, increase the radius of teeth fillet will decrease the danger of plain fatigue but increase the danger of fretting fatigue at the same time. IMW complex cycloid profile teeth are more sensitive to fretting fatigue compared with involute spline profile and the danger of plain fatigue at teeth root is greatly decreased. There's a 'competition' of plain fatigue and fretting fatigue in spline teeth, which can be weighted by profile optimization.

5 References

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